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► To cite this version:

Frédéric Kuznik, Loïc Frayssinet, Jean-Jacques Roux, Lucie Merlier. Calculation of heating and cooling energy loads at the district scale: Development of MoDEM, a modular and technologically explicit platform. *Sustainable Cities and Society*, 2022, 83, pp.103901. 10.1016/j.scs.2022.103901 . hal-04255669

HAL Id: hal-04255669

<https://hal.science/hal-04255669v1>

Submitted on 22 Jul 2024

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Calculation of heating and cooling energy loads at the district scale: development of MoDEM, a modular and technologically explicit platform

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Abstract

The rationalization of energy at the district scale requires the development of numerical tools capable of simulating not only the energy demand, but also energy loads at such a scale. However, such simulation remains difficult because of the computational cost and lack of reliable data. A common solution to both these problems is to simplify the model, generally at the expense of accuracy. To overcome these problems, a specific modeling and simulation platform called Modular District Energy Model (MoDEM) is developed. This platform enables the calculation of the heating and cooling load curves of each building, integrating the interactions between the buildings taking into account longwave radiative heat transfers between buildings external surfaces. Moreover, with different levels of models included in its calculation engine, MoDEM also enables the testing of modeling assumptions. MoDEM can also handle the geographical information system geometry and detailed

solar radiation calculation. To validate the application of MoDEM, a district in Paris is modeled, comprising 900 flats built in the 1930s. The results demonstrate that 1) various models have little impact on energy consumption and 2) some physical phenomena usually not modeled appropriately, such as the longwave radiative exchange between buildings, can no longer be neglected while considering the load curve. It is worth mentioning that MoDEM is based on a co-simulation layer allowing parallel computing. From a broader point of view, this specific feature enables the easy and computationally efficient integration of various models like, for instance, specific electricity consumption, renewable energy production, grid management simulation and energy storage.

Keywords: Heating Energy Loads, Cooling Energy Loads, Technologically Explicit Model, MoDEM Platform, District modeling

1. Introduction

The building sector plays a major role in current environmental and urban growth dynamics, especially regarding the development or retrofiting of districts. Therefore, tools are required to guide the choices and practices of city decision makers, urban planners, and building designers [1–5]. As current challenges particularly concern the design of energy conservative and efficient buildings and districts, the availability of reliable dynamic energy models suitable for urban studies appears to be essential, notably regarding:

- the demand side management of urban district networks [6, 7],
- the optimization of operation strategies for district systems [8–10],

- the design of smart heating/cooling grids [11–14],
- and the integration of waste heat or renewable energies [15–17].

To eventually address these operational goals, which rise different scientific challenges, researchers have developed different approaches. In particular, as a large part of the energy consumed in cities is used to provide comfortable indoor thermal conditions, Figure 1 depicts the main approaches of simulating the heating and cooling loads of urban buildings in the literature. From the building to the urban scale, four main types of approaches can be observed:

[Figure 1 about here.]

- **Building energy models (BEMs)** developed using usual programs, such as TRNsys or Energy_Plus, can be adapted to consider some effects of the urban environment, such as the urban heat island intensity, in the computation of the energy consumption of buildings [18–26]. Nevertheless, coupling to the urban environment is usually tricky as BEMs were originally designed for studying a single isolated building. Furthermore, their direct use at the district and city scales remains difficult because of the associated computational cost.
- **Urban building energy models (UBEMs)** aim at comprehensively considering interactions between a building and its urban environment and microclimate. Corresponding tools (SOLENE-Microclimate [27, 28], EnviBatE [29] or 3D CAD-based coupled simulation tool [30, 31])

are often thermo-radiative tools that can be coupled with computational fluid dynamics. However, UBEMs demand a generally high computational cost because of the relatively detailed modeling of external physical phenomena and transfers. Therefore, it is generally difficult to perform year-round simulations of numerous buildings in a reasonable time, especially when using CFD.

- **District energy models (DEMs)**, such as CitySim [32], the successor of SUNtool [33], Smart-E [34], DIMOSIM [35], Virtual PULSE [36], AMBASSADOR Project [37], or OpenIDEAS [38] aim at simultaneous, but relatively rapid, computation of energy loads of numerous urban buildings. Their objective is to help decision makers understand the flexibility of building demand, optimize the global district energy system or the grid management, or perform integrated district energy simulations at the building and neighborhood levels. However, the computational effectiveness of DEMs is generally achieved at the cost of a high simplification of interactions between buildings and their surroundings. Nevertheless, computational costs can also be reduced through mathematical reduction of equations describing the heat transfers in a district, as in [39]. However, the loss of explicitness during the reduction procedure remains a major issue.
- Finally, **energy consumption models (ECMs)** rely on either a *top-down* approach when utilizing historic aggregated energy values and regressions, or a *bottom-up* approach when extrapolating the estimated energy consumption of a representative set of buildings [40]. Because

of their basic assumptions, ECMs cannot be used to assess heating and cooling loads.

This classification highlights the main problems underlying the development and use of energy models for studying urban issues: (1) representativeness of the considered models, (2) rapidly increasing computational costs of detailed energy simulations at the urban scale, and (3) lack of relevant data/parameters to feed the corresponding models. Consequently, simplifications are generally mandatory, especially with respect to the modeling of radiative transfers and microclimate, as well as the building envelope [2]. However, these simplifications can significantly affect the reliability and effectiveness of simulations, especially when addressing power load problems. In addition, care should be given to the initialization of simulation depending on the modeling strategy.

Given the above-mentioned common limitations of BEMs, UBEMS, DEMs, and ECMs and current challenges linked with the design of energy efficient buildings and districts, the present work suggests a flexible and modular DEM, in which:

- geometrical models can be generated automatically from Geographical Information System (GIS) to ease the modeling pre-process,
- each building model can be explicitly described with sufficient details to account for the properties of its building envelope and systems,
- the embedded BEMs can integrate the diversity of occupant behaviors,
- interactions between each building and the surroundings can be taken into account,

- and the output can be presented as, at least, the heating and cooling loads of each building, and by extension, the heating and cooling loads of the district/city.

In addition, the modularity of the developed DEM implies that it should be able to integrate different levels of details—model adaptations—depending on the available input data and computational resources.

These different features were integrated in the developed Modular District Energy Model (MoDEM) platform, which is especially suited to the study of residential districts. Regarding the above-mentioned modeling challenges as well as the research challenges highlighted in [3], the MoDEM platform will relevantly help the design and operation of low-energy cities, mainly from a district energy point of view, thanks to its following original feature. Based on a bottom-up and techno-explicit approach, the MoDEM platform gathers in a modular workflow diverse input data and multi-scale engineering modelings capable of simulating the heating and cooling power load curve of districts, taking into account inter-building effects, thanks to the use of parallel and interoperable new generation computational tools based on Modelica and functional mockup interface (FMI) standards (IEA EBC - International energy agency, energy in buildings and communities programme - Annex 60).

The general methodology of MoDEM is presented in Section 2. Reliable calculations requiring reliable input data and relevant physical modeling, data sources are detailed in Section 3, and the physical models are described in Section 4. Section 5 presents a case study of MoDEM, highlighting the possibilities offered by the developed platform. Finally, the conclusions are

drawn in the last section.

2. Methodology: the genesis of MoDEM

The structure of the MoDEM toolchain is built on the most promising tools developed for the new generation of BEMs [41] and includes an upscaling level to build and simulate the DEM. A sketch of the MoDEM toolchain showing the different links between the physical models, input data, and simulation tools is depicted in Fig. 2.

[Figure 2 about here.]

The first step in the toolchain is to automatically generate the BEMs. The generation of the model geometry is based on GIS and is performed using MERRUBI¹ tool [42, 43], via SketchUp². A detailed .xml (.bsp) file of the geometry is then created, and a form factor table is generated using the ray tracing method. Then, BEMs are generated for each building using the BuildSysPro Modelica library [44, 45], which is based on a 0D/1D approach, and a finite volume method for conduction. This EDF³ R&D's library has been validated with respect to experimental data, especially regarding highly energy efficient buildings [46, 47], and used to study the effects of urban environments and building external boundary conditions on the energy behavior of lowly or highly energy efficient buildings [48, 49].

¹MERUBBI project available via <https://anr.fr/Projet-ANR-13-VBDU-0007> [French]

²<https://www.sketchup.com/fr>

³French electricity company

Each created BEM is basically an assembly of sub-models, automatically generated and connected to other sub-models to enable the modeling of different levels of details (BEM adaptations); each geometric element is extracted from the .xml file and parameterized with data sources or default values. BEMs are then run using the Dymola environment. The 'DASSL' time step adaptation solver is used to solve the Modelica equations. The basic observational time step is fixed to 1 h, considering the common time step of weather files.

The second step is to simulate different BEMs comprising the DEM. To account for the potentially substantial computational costs induced by the consideration of building details and the large number of buildings within a district, the DESs are distributed.

To this end, the global problem is converted using Dymola into functional mockup units (FMUs), each of which encompasses both a BEM and a numerical solver according to the FMIs [50], an open-source community-driven standard developed for coupled simulation and model exchanges. The distributed co-simulations of the FMUs are managed via a specific script (*.dng) using Distributed Architecture for Controlled CO-SIMulation (DACCOSIM), an FMI compatible master algorithm generator [51], which enables direct integration of different levels of building interactions. For this purpose, data exchanges can be performed between FMUs by Daccosim every 900 s.

All the different parts of the platform are interlinked using specific Python scripts. In terms of computational performance, a typical BEM lasts for 2 min on an 8-core computer with 2.5 GHz and 8 GB RAM, and a DEM including 23 embedded BEMs lasts for 30 min on the same computer. A

specific Python application called DacRun enables cluster computations.

3. Data sources: The fuel of MoDEM

3.1. Foreword

Heating and cooling loads of a district are inherently dependent on its geometry, the thermo-physical properties of its construction materials and the behavior of inhabitants. Therefore, district scale energy modeling requires various information in terms of the district composition and use, which are often not well known. In addition, when existing, related information is generally made available by very different sources, which implies very different formats of data and levels of detail. Therefore, the MoDEM platform is capable of considering different data sources and enriching the integrated data to complete the required inputs of techno-explicit models.

3.2. Geometrical data

The generation of a DEM obviously requires various information about the district, which is often an issue. Nevertheless, the management of district scale data is currently growing at a rapid pace, particularly with the use of GIS. GIS data are based on geometrical data that represent a specific territory, which are completed with various structured semantic information, such as type description, use, and construction period. Various cities around the world are developing GISs, often providing open access to databases⁴. However, these data often exhibit topologically unclosed geometries, multiple facets in collinear surfaces, or incorrect building splitting (see [52] for

⁴see for example <https://data.grandlyon.com/>.

instance). In addition, GIS data often do not provide information regarding the construction materials of buildings. Thus, given the current limitations of GIS, the MoDEM platform only uses the geometrical data of GISs, which already comprise details of the building zones (volume) and enclosure surfaces (area, orientation and adjacent zones).

3.3. Thermo-physical data

As information regarding the construction materials of buildings is generally not directly available in usual GIS data, the MoDEM platform deduces them from the French typology of residential buildings defined in the European TABULA ⁵ project [53]. The aim of this project was to classify European national building stocks and to estimate their energy consumption and the related potential energy savings. The suggested typology is classified into four building categories (single-family house, terraced house, multi-family house, and apartment block) and ten construction periods. A set of reference buildings is proposed for each building type along with a description of the building materials and the system used, which enables the characterization of existing buildings according to their construction period and morphology.

In addition, the typology provides U-values of facade elements. As the material thickness is not always available in the typology, the layers' thickness or thermal conductivity need to be specified complementarily to match the U-value and build the BEM. Other properties of the element surfaces, such as surface emissivity and albedo, also need to be specified. In this manner,

⁵<http://episcope.eu/building-typology/>

the building information extracted by the MoDEM platform is enriched with different thermo-physical parameters deduced from the usual BEMs values.

3.4. Occupant information

When considering the load curve at the district scale, the maximum load peak is generally lower than the sum of the individual maximum peaks of each consumer due resulting in generating diversity [54]. This phenomenon is related to the non-concomitance of individual load peaks as consumers do not perform the same tasks at the same time and have different comfort criteria. Thus, there is no unique reference schedule in terms of occupant behavior, which influences the internal heat gains (depending on the occupancy, devices used, and other factors) and the settings of energy systems (temperature set-point) to be specified in the BEMs.

To take occupant related diversity into account in DEMs, dynamic scenarios can be obtained using agent-based models, such as [55] and [56] or stochastic modeling. The MoDEM platform acquires dynamic scenarios from the SMACH tool, an EDF R&D agent based model [57, 58], more precisely. Based on the monitoring of different family types and city statistical data (type of housing, socio-professional category, etc.) this tool can generate statistically representative housing scenarios for each person in a family with a time-step of 1 min, considering interactions due to housing conditions, i.e., comfort.

As a starting point for MoDEM, a set of 1,000 monthly scenarios aggregated at the housing level were generated based on the statistics on Lyon, France. These scenarios contain the hourly evolution of the number of occupants and the temperature set-point, as well as descriptions of the housing

and household. Being quasi periodic, the scenarios last only one month and can be repeated to limit the computing cost. As only the shape of the building is known from the GIS extraction and not the composition of housings, aggregated scenarios at the building scale are then generated by randomly assembling the housing scenarios until the total floor area of the housings nearly corresponds to the estimated floor area of the building. The number of occupants is summed, and the set-point temperature is weighted by the floor area and averaged. Then, in the BEM, the internal heat gains are modulated by the occupancy ratio, and the set-point temperature is directly imposed

4. Energy models: The engine of MoDEM

4.1. Foreword

Heating and cooling loads are driven by heat transfers, which need to be relevantly modeled to obtain meaningful simulation outputs. The corresponding physical equations representing conduction, convection, and radiation can be written as a set of differential-algebraic system of equations. The common issue in all the tools dedicated to district load calculations remains the level of detail in the modeling, i.e., the representativeness of the physical phenomena taken into account. Indeed, the accuracy of modeling is potentially higher with more details, but it is also more computationally expensive and requires more input data. Accordingly, the MoDEM platform is capable of testing different levels of modeling through “adaptations” to estimate their effects on simulation results and thus, it can evaluate the reliability of the developed DEM in predicting district energy loads.

4.2. Building Energy Model

The BEMs are created using the BuildSysPro Modelica library. Modelica is basically an object-oriented, equation-based, and acausal programming language that was developed to support all engineering domains. Hence, it is particularly suited for developing a flexible and techno-explicit DEM, such as MoDEM. The structure and parametrization of the Modelica model resulting from the automatic generation of the BEMs (Sec. 2) depend on the adaptations considered. This modularity of the model implies different sub-models and different connections between them, which need to be compatible regardless of the adaptation combination.

From a modeling point of view, the MoDEM platform includes the different options listed below for the BEMs:

- Wall discretization for conductive heat transfers: coarse resolution, e.g., a single node per wall [$Cond-\tau_{large}$], or a finer spatial resolution [τ_{small}], where τ is the characteristic time in s
- Building zoning: monozone [$Zoning - 0$], multizone by floor [$-lvl$], by outer wall orientation [$-ori$], or both [$-comb$]
- Controlled physical quantity: the indoor air temperature [$Control - 0$] or operative temperature [-1]
- Distribution of the transmitted solar flux: on the floor [$trSol - 0$] or proportionally distributed on the walls depending on their area [-1]
- Modeling of internal longwave radiative exchanges: linearized exchanges based on the indoor air temperature [$intLW - 0$] or operative temperature [-1]

- Integration of the internal thermal mass of the building: modeling of internal walls [*inertia* – 0] or otherwise [–1]
- Modeling of external convective heat transfers: constant convective heat transfer coefficient (CHTC) [*CHTC* – 0] or wind-dependent formulation ($CHTC = 4 + 4v$), where v is the normal projected wind velocity [–1]
- Modeling of external longwave heat transfers: linearized formulation [*extLW* – 0] or complete formulation derived from the Stefan Boltzmann law [–1]
- General representation of the envelope: differentiation of walls depending on their properties [*EqEnv* – 0] or one equivalent thermal wall [–1];

Table 1 summarizes and illustrates most of these different model options.

[Table 1 about here.]

4.3. District Energy Model

Similarly to BEM, which is an assembly of sub-models (walls, air zones...), DEM is an assembly of building energy models. However, the DEM is not written in the Modelica language as the resulting model may be too computationally intensive to simulate. From a computational point of view, it is clearly more beneficial to distribute the BEM simulations, notably because they consist of numerous problems of very similar computational weight that are relatively weakly linked. This option is a really new methodology developed to overcome weaknesses of most existing approaches.

From a physical modeling point of view, the DEM also includes different options:

- Integration of solar masks and multi reflection: received solar flux directly derived from the weather file [*Solar* – 0] or estimated using ray tracing [–1]. The main difference between those 2 options lies in the inclusion of the urban morphology to assess the incoming solar radiation on each building wall/roof.
- Estimation of longwave radiative heat transfers: ground and building surface temperature approximated by the outdoor air temperature [*LWRad* – 0] or estimated by energy simulation and the complete longwave radiative exchange formulation derived from the Stefan-Boltzmann law[–1]. In most of building energy simulation tools, the external infrared radiation exchange is not taken into account but only estimated using the external air temperature. Of course, such assumption is far from being realistic, especially in urban area. That is the reason why we propose an option using the other buildings external surface temperature to assess the longwave radiation exchange in a physical way, i.e. using the Stefan-Boltzmann law.
- Consideration of adjoin buildings: adiabatic half party walls [*ajoin* – 0] or coupled interface [–1]. This feature deals with the way adjoined buildings are taken into account. The first option lies on a heat transfer symmetry assumption leading to consider a no-heat flux at the middle of the adjoined wall. In the second option, a real coupling is made.

These different model options are also summarized and illustrated in Table 1.

5. Case study: outputs from MoDEM

5.1. Model description

To illustrate the possibilities of MoDEM, especially when used as a support tool to relevantly choose a level of detail for a DEM with respect to the targeted application, a case study was developed. Figure 3 depicts the selected use case for 23 apartment buildings with the same typology in a district in Paris. This district comprises approximately 900 flat units built in the 1930s. Table 2 presents the main thermal properties of the buildings according to the TABULA database, which correspond to relatively thermally inefficient buildings.

[Figure 3 about here.]

[Table 2 about here.]

For the modeling, geometric data were taken from the IGN⁶ database called BD TOPO. The 23 buildings were connected to each other with adjoining walls (indicated in blue in Figure 3). The weather file of Paris Montsouris was selected for the study. Considering the building typology and regional climate, the case study focused on heating loads, with a temperature set-point fixed at 19°C.

⁶National geographic Institute

To evaluate the effects of model adaptations, a reference model was defined with a characteristic time τ of 900 s for conduction, basic BEM options detailed in Table 1 taken as [-0], and DEM options taken as [-1].

Figure 4 depicts the simulation results in terms of year-round energy loads for this reference model. The heating period ranges from mid-September to mid-June, and the maximum heating occurs during January and February. In addition to these seasonal trends, the heating load curve also demonstrates daily variations, evidencing the sensitivity of buildings to general climatic conditions, as well as more intermittent solicitations, such as solar heating.

[Figure 4 about here.]

5.2. Results analysis: Effects of model adaptations

Based on the reference model, the different options of BEM[-1] and DEM[-0] presented in Table 1 were simulated. Note that [*Zoning* - 1] corresponds to a division of the largest buildings with respect to the main orientation, and not floor-wise. This zoning generated 33 zones with 12 adjoining walls, represented by blue and red in Figure 3. This configuration was considered to study the effect of adjoining walls. Regarding the effects of model adaptations, Fig. 5 depicts three indicators reflecting the relative effect of different BEM and DEM adaptations in terms of the heating load difference between the reference model and the selected model adaptation:

- the mean value $m(\cdot)$, which quantifies discrepancies in terms of annual energy predictions,
- the standard deviation $\sigma(\cdot)$, which quantifies discrepancies in terms of power fluctuation amplitudes and phase shifts,

- and the minimal and maximal values $M(\cdot)$, which quantify discrepancies in terms of their ability to handle particular events.

[Figure 5 about here.]

Results demonstrate that low wall discretization has little effect on the mean and standard deviation, but deviation may be more important locally. Indeed, low wall discretization delays the building response to dynamic solicitations, especially those linked with rapid solar loads. Regarding other BEM adaptations, the results highlight that modeling multizone buildings does not significantly alter the prediction of heating loads. Controlling the operative temperature instead of the air temperature generally increases the simulated heating loads. This trend is explained by the fact that the wall temperature is lower than the air temperature. Uniformly distributing the solar flux over different walls has little effect on the simulation results. This conclusion may be explained by the higher availability of solar heating but lower heat storage, which balance each other. For the same reason as the control temperature, using the operative temperature instead of the air temperature to estimate longwave heat transfers decreases the predicted heat losses with a typical daily pattern. The deviation is the lowest around mid-day because the operative temperature is closer to the air temperature due to solar heating. The mean and standard deviations of this adaptation are the highest among the tested adaptations. The maximum deviation is also substantial. Neglecting internal walls tends to decrease the simulated floating temperature periods and increase the heating needs, with a dynamic temporal pattern. Heating is more necessary after sunny periods because

of the absence of a buffer effect. Considering wind-dependency, the external CHTC tends to decrease the predicted heating needs as the estimated CHTC is generally lower than the constant default value. This effect is significant, both in terms of mean and standard deviation. It is also the most influential model adaptation with respect to the maximum deviation. This effect has no specific temporal pattern as wind does not depend on solar loads in the model. Not considering the linearized formulation of the longwave external exchanges also induces lower heat losses and thus, heating needs estimates. However, this effect is less important than the effect of the CHTC. Finally, considering an equivalent envelope does not change the general trends to a large extent, but causes significant local deviation as the dynamic behavior of the envelope is altered by the equivalence assumption.

Regarding DEM adaptations, almost only the adaptation of the short-wave heat flux appeared to affect the simulation results. Indeed, accounting for solar masks increases the estimates of heating needs because of less solar heating, leading to substantial local deviations. The effects of using BEMs results and taking the thermal balance of adjoining walls into account to estimate longwave radiative heat exchanges appear to be negligible. Nonetheless, these results need to be modulated by the facts that the present study focuses on heating needs and that adjoining wall surfaces are extremely small in comparison with the total building envelope area. Thus, the present results may be case-specific.

Hence, this case study suggests that if the output of interest is the annual heating energy demand of an old residential district, usual model adaptations are acceptable, with the exception of assimilating the indoor surface

temperature to the indoor air temperature to compute longwave radiative heat exchanges, and neglecting the wind-dependency of the external CHTC. Conversely, when aiming to study the load curve, considering that the operative temperature is controlled, the fine discretization of walls—even more if considering an equivalent envelope—as well as the modeling of internal walls and solar shading appear mandatory, as the maximum deviation criteria are also restrictive. Thus, a control model would also be required.

5.3. Results analysis: Effects of diversity

In real district, the sum of the individual peaks of demands is higher than the global peak demand: this phenomenon is called diversity. The probable source of diversity that may affect building energy behaviour at the district scale is the variety of building shapes, construction materials, occupant behaviours... The variety of shape both affects the building spatial characteristics and its weather-induced thermal loads (notably solar and radiant temperature in our model).

In order to quantify diversity, the difference between the sum of energy demand and the global energy demand is calculated; this difference being time series. All the indicators are normalized using the global demand. The indicators used to assess diversity are (see section 5.2 for more information about their meaning):

- the mean value $m(\cdot)$,
- the root mean square $rm(\cdot)$,
- the standard deviation $\sigma(\cdot)$,

- the maximum difference $M(\cdot)$.

Figure 6 depicts the relative effects of diversity at the district scale, completing the results analysis. The diversity relative effect is higher when the effects are extremely low (notably when increasing the wall discretization or neglecting heat transfers between adjacent buildings). This effect is not phenomenological but rather because the effect tends toward zero.

Regarding the maximal deviation, the diversity relative effect is generally lower than 10 % for the most impactful adaptations (Sec. 5.2). On the contrary, considering distributed solar fluxes or neglecting solar masks or external longwave radiation between buildings have particularly high diversity effects (38, 16, and 39 % respectively), probably because they are the most shape-related adaptations.

In general, the diversity quantified for the standard deviation is approximately twice lower than that for the maximal deviation, except for [*Inertia-1*], where it is almost thrice higher. Hence, the maximal deviations caused by IntInertia are nearly synchronous, but not globally applicable to the others.

[Figure 6 about here.]

6. Discussion

The MoDEM platform aims to take advantage of existing tools and software that are currently known to have important developments (Modelica, FMU), particularly for building energy simulations at the district scale [59], to efficiently and automatically create modular DEMs and ease the interoperability of the platform. This developed tool chain enables the simulation

of heating and cooling energy loads of a district considering the main interactions and couplings between buildings. Moreover, the distribution of the simulation facilitates the mitigation of computational time. In contrast to the common use of simplified models at the district scale, this platform favors the use of detailed models at the district scale and limits the need for simplifications because of up-scaling. The distribution also eases large scale simulation and parametric analysis.

Although the generated district models were based on the tried and tested BuildSysPro library, and the aim of proposing the platform was mainly to discuss the suitability of different model adaptations, it is worth mentioning that the tested MoDEMs were not validated against experimental data. Nevertheless, a MoDEM was compared with another DEM, Smart-E [60] considering the same use case as in Sec. 5 to identify the impact of different modeling choices, particularly on the power curve [61]. These models were generated independently in each platform and run for the same weather file.

The simulation results demonstrated noticeable deviations. The annual consumption was computed as nearly twice higher with MoDEM. These deviations can be explained by the means of accounting for the geometry; MoDEMs are based on real geometry extracted from the GIS, i.e., explicit building models, whereas Smart-E comprises housing thermal models built from the statistics of the district. In particular, the resulting differences between the two approaches mainly result from the consideration of un-heated spaces in Smart-E, contrary to MoDEM. This comparison shows evidence of modeling bias due to the use of different modeling approaches, but reinforces the physical modelling approach. Indeed, the comparison highlights the need

for information on the suitability of modeling choices, particularly at short time steps, which is the aim of this study.

Furthermore, these results also highlight the need of a comparative model validation test for district energy simulations (DESTEST), i.e. a common district case study, as introduced in the IEA EBC Annex 60 to support DEM development. Although validation is generally mandatory to support any numerical model development, such a DESTEST would overcome several major difficulties of addressing district-scale reliable and high-resolution energy simulations, such as:

- access to detailed and accurate input data, such as the geometry, system efficiency, materials, and composition of housings and households. Efforts on the development of GIS and more particularly of standardized CityGML databases coupled with building information models would certainly help energy modelers;⁷
- access to the quantity of interest, currently the load curve,
- as well as the integration of several complex and diverse aspects that the model needs to handle to reproduce conditions as realistically as possible, i.e., the envelope, systems, local climate, and particularly occupant behaviors for internal heat gains due to electrical devices that are currently only related to occupancy and occupant behavior, which is non-coupled with current thermal comfort, etc.

⁷he main formats used are gbXML and IFC ⁸. The junction between BIM and GIS is in progress [62]; however, as BIMs are mainly available for new buildings, information on existing buildings is highly lacking, which is generally critical for DEMs.

Thus, facing DEM challenges relies not only on adaptations, but also on the use of efficient large-scale numerical resources and data collection. Therefore, improvements of the MoDEM platform, and more largely of DES platform, requires cooperation with other scientific fields, including micro-meteorology to improve the integration of environmental effects, computer sciences to improve and speed-up numerical processes, geomatics for GIS management, and data sciences to define indicators and analyze results.

7. Concluding remarks

The first objective of our work was to develop the MoDEM platform with the specific requirements detailed along the manuscript. But, beside the modularity of MoDEM and its capability to handle various models via the co-simulation layer, different findings have been highlighted. In particular, the energy consumption few depends on the model choice, among those implemented in the platform. The diversity also few depends on the modeling assumption among those implemented in the platform. On the contrary, the correct estimation of heating and cooling loads requires an appropriate discretization of the walls as well as an appropriate modeling of longwave radiative heat transfer between external building walls.

In addition, the developed platform aims to take advantage of existing tools and software to efficiently and automatically create modular district energy models. In its current state, the platform mainly focuses on envelope modeling, but future improvements are needed to better account for the effective composition of districts, including tertiary buildings, system regulation, and occupant behaviors, which are still roughly modeled, and to integrate

micro-climate models.

Finally, the results demonstrate that studying the power at the district scale necessitates the use of detailed models, but the district scale smoothens this constraint. Hence, the critical point is to define indicators related to the expected simulation objective in order to adapt the level of detail of the BEM and DEM and the input data such as suggested in the present study.

8. Nomenclature

- BEM : building energy models
- CAD : computer aided design
- CFD: computational fluid dynamics
- CHTC : convective heat transfer coefficient
- DEM : district energy model
- ECM : energy consumption model
- FMI : functional mockup interface
- FMU : functional mockup unit
- GIS : geographical information system
- MoDEM : modular district energy model
- UBEM : urban building energy model

Acknowledgments

The authors want to thank EDF (Electricity of France) R&D for its financial, scientific, and technical support in the framework of the EDF-CETHIL joint laboratory BHEE (Highly Efficient Energy Buildings).

References

- [1] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, *Renewable and Sustainable Energy Reviews* 16 (6) (2012) 3847–3866. doi:10.1016/j.rser.2012.02.047.
- [2] L. Frayssinet, L. Merlier, F. Kuznik, J.-L. Hubert, M. Milliez, J.-J. Roux, Modeling the heating and cooling energy demand of urban buildings at city scale, *Renewable and Sustainable Energy Reviews* 81 (2018) 2318–2327. doi:10.1016/j.rser.2017.06.040.
- [3] T. Hong, Y. Chen, X. Luo, N. Luo, S. H. Lee, Ten questions on urban building energy modeling, *Building and Environment* 168 (2020) 106508. doi:<https://doi.org/10.1016/j.buildenv.2019.106508>.
URL <http://www.sciencedirect.com/science/article/pii/S0360132319307206>
- [4] A. Sola, C. Corchero, J. Salom, M. Sanmarti, Multi-domain urban-scale energy modelling tools: A review, *Sustainable Cities and Society* 54 (2020) 101872. doi:<https://doi.org/10.1016/j.scs.2019.101872>.

- [5] Y. Q. Ang, Z. M. Berzolla, C. F. Reinhart, From concept to application: A review of use cases in urban building energy modeling, *Applied Energy* 279 (2020) 115738. doi:<https://doi.org/10.1016/j.apenergy.2020.115738>.
- [6] H. Cai, C. Ziras, S. You, R. Li, K. Honor, H. W. Bindner, Demand side management in urban district heating networks, *Applied Energy* 230 (2018) 506–518. doi:[10.1016/j.apenergy.2018.08.105](https://doi.org/10.1016/j.apenergy.2018.08.105).
- [7] S. Eggimann, J. W. Hall, N. Eyre, A high-resolution spatio-temporal energy demand simulation to explore the potential of heating demand side management with large-scale heat pump diffusion, *Applied Energy* 236 (2019) 997–1010. doi:[10.1016/j.apenergy.2018.12.052](https://doi.org/10.1016/j.apenergy.2018.12.052).
- [8] N. Deng, G. He, Y. Gao, B. Yang, J. Zhao, S. He, X. Tian, Comparative analysis of optimal operation strategies for district heating and cooling system based on design and actual load, *Applied Energy* 205 (2017) 577–588. doi:[10.1016/j.apenergy.2017.07.104](https://doi.org/10.1016/j.apenergy.2017.07.104).
- [9] E. Guelpa, S. Deputato, V. Verda, Thermal request optimization in district heating networks using a clustering approach, *Applied Energy* 228 (2018) 608–617. doi:[10.1016/j.apenergy.2018.06.041](https://doi.org/10.1016/j.apenergy.2018.06.041).
- [10] D. Wang, Y. qiang Zhi, H. jie Jia, K. Hou, S. xi Zhang, W. Du, X. dong Wang, M. hua Fan, Optimal scheduling strategy of district integrated heat and power system with wind power and multiple energy stations considering thermal inertia of buildings under different

- heating regulation modes, *Applied Energy* 240 (2019) 341–358. doi:10.1016/j.apenergy.2019.01.199.
- [11] H. Gadd, S. Werner, Heat load patterns in district heating substations, *Applied Energy* 108 (2013) 176–183. doi:10.1016/j.apenergy.2013.02.062.
- [12] G. T. Ayele, P. Haurant, B. Laumert, B. Lacarriere, An extended energy hub approach for load flow analysis of highly coupled district energy networks: Illustration with electricity and heating, *Applied Energy* 212 (2018) 850–867. doi:10.1016/j.apenergy.2017.12.090.
- [13] H. Gadd, S. Werner, Daily heat load variations in swedish district heating systems, *Applied Energy* 106 (2013) 47–55. doi:10.1016/j.apenergy.2013.01.030.
- [14] J. Hennessy, H. Li, F. Wallin, E. Thorin, Towards smart thermal grids: Techno-economic feasibility of commercial heat-to-power technologies for district heating, *Applied Energy* 228 (2018) 766–776. doi:10.1016/j.apenergy.2018.06.105.
- [15] F. Buhler, S. Petrovic, K. Karlsson, B. Elmegaard, Industrial excess heat for district heating in denmark, *Applied Energy* 205 (2017) 991–1001. doi:10.1016/j.apenergy.2017.08.032.
- [16] R. Renaldi, D. Friedrich, Techno-economic analysis of a solar district heating system with seasonal thermal storage in the uk, *Applied Energy* 236 (2019) 388–400. doi:10.1016/j.apenergy.2018.11.030.

- [17] H. Rehman, J. Hirvonen, K. Siren, Performance comparison between optimized design of a centralized and semi-decentralized community size solar district heating system, *Applied Energy* 229 (2018) 1072–1094. doi:10.1016/j.apenergy.2018.08.064.
- [18] M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, D. Assimakopoulos, On the impact of urban climate on the energy consumption of buildings, *Solar Energy* 70 (3) (2001) 201–216, urban Environment. doi:10.1016/S0038-092X(00)00095-5.
- [19] M. Kolokotroni, Y. Zhang, R. Watkins, The london heat island and building cooling design, *Solar Energy* 81 (1) (2007) 102–110. doi:10.1016/j.solener.2006.06.005.
- [20] M. Assimakopoulos, G. Mihalakakou, H. Flocas, Simulating the thermal behaviour of a building during summer period in the urban environment, *Renewable Energy* 32 (11) (2007) 1805–1816. doi:10.1016/j.renene.2006.08.003.
- [21] S. Oxizidis, A. Dudek, A. Papadopoulos, A computational method to assess the impact of urban climate on buildings using modeled climatic data, *Energy and Buildings* 40 (3) (2008) 215–223. doi:10.1016/j.enbuild.2007.02.018.
- [22] J. Stromann-Andersen, P. Sattrup, The urban canyon and building energy use: Urban density versus daylight and passive solar gains, *Energy and Buildings* 43 (8) (2011) 2011–2020. doi:10.1016/j.enbuild.2011.04.007.

- [23] D. Kesten, A. Tereci, A. M. Strzalka, U. Eicker, A method to quantify the energy performance in urban quarters, *HVAC&R Research* 18 (1–2) (2012) 100–111. arXiv:<https://www.tandfonline.com/doi/pdf/10.1080/10789669.2011.583307>, doi:10.1080/10789669.2011.583307.
- [24] X. Yang, L. Zhao, M. Bruse, Q. Meng, An integrated simulation method for building energy performance assessment in urban environments, *Energy and Buildings* 54 (2012) 243–251. doi:10.1016/j.enbuild.2012.07.042.
- [25] J. Allegrini, V. Dorer, J. Carmeliet, Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings, *Energy and Buildings* 55 (2012) 823–832, cool Roofs, Cool Pavements, Cool Cities, and Cool World. doi:10.1016/j.enbuild.2012.10.013.
- [26] J. Allegrini, V. Dorer, J. Carmeliet, Analysis of convective heat transfer at building facades in street canyons and its influence on the predictions of space cooling demand in buildings, *Journal of Wind Engineering and Industrial Aerodynamics* 104–106 (2012) 464–473, 13th International Conference on Wind Engineering. doi:10.1016/j.jweia.2012.02.003.
- [27] J. Bouyer, C. Inard, M. Musy, Microclimatic coupling as a solution to improve building energy simulation in an urban context, *Energy and Buildings* 43 (7) (2011) 1549–1559. doi:10.1016/j.enbuild.2011.02.010.

- [28] A. Gros, E. Bozonnet, C. Inard, M. Musy, Simulation tools to assess microclimate and building energy - a case study on the design of a new district, *Energy and Buildings* 114 (2016) 112–122, sI: Countermeasures to Urban Heat Island. doi:10.1016/j.enbuild.2015.06.032.
- [29] A. Gros, E. Bozonnet, C. Inard, Cool materials impact at district scale - coupling building energy and microclimate models, *Sustainable Cities and Society* 13 (2014) 254–266. doi:10.1016/j.scs.2014.02.002.
- [30] J. He, A. Hoyano, T. Asawa, A numerical simulation tool for predicting the impact of outdoor thermal environment on building energy performance, *Applied Energy* 86 (9) (2009) 1596–1605. doi:10.1016/j.apenergy.2008.12.034.
- [31] T. Asawa, A. Hoyano, K. Nakaohkubo, Thermal design tool for outdoor spaces based on heat balance simulation using a 3d-cad system, *Building and Environment* 43 (12) (2008) 2112–2123. doi:10.1016/j.buildenv.2007.12.007.
- [32] D. Robinson, F. Haldi, J. Kampf, P. Leroux, D. Perez, A. Rasheed, U. Wilke, Citysim: Comprehensive micro-simulation of resource flows for sustainable urban planning, in: *Eleventh International IBPSA Conference*, 2009, pp. 1083–1090.
- [33] D. Robinson, N. Campbell, W. Gaiser, K. Kabel, A. Le-Mouel, N. Morel, J. Page, S. Stankovic, A. Stone, Suntool - a new modelling paradigm for simulating and optimising urban sustainability, *Solar Energy* 81 (9)

- (2007) 1196–1211, cISBAT 2005. doi:10.1016/j.solener.2007.06.002.
- [34] T. Berthou, B. D. P. Riviere, P. Stabat, D. Casetta, D. Marchio, Smart-e: A tool for energy demand simulation and optimization at the city scale, in: 14th International Conference of IBPSA, Hyderabad, India, 2015.
- [35] P. Riederer, V. Partenay, N. Perez, C. Nocito, R. Trigance, T. Guiot, Development of a simulation platform for the evaluation of district energy system performance, in: 14th International Conference of IBPSA, Hyderabad, India, 2015.
- [36] M. Heidarinejad, N. W. Mattise, M. Dahlhausen, S. K. Nikkho, J. Liu, S. Gracik, K. Liu, K. Sharma, H. Zhang, J. R. Wentz, M. S. Roudsari, J. S. G. Pitchurov, Urban scale modeling of campus building using virtual pulse, in: 14th International Conference of IBPSA, Hyderabad, India, 2015.
- [37] P. Beguery, P. Paum, N. Rousset, F. Bourry, A. Wantier, Simulation for the evaluation of energy management algorithms at the district level - example of use case from the ambassador project, in: 14th International Conference of IBPSA, Hyderabad, India, 2015.
- [38] R. Baetens, R. D. Coninck, F. Jorissen, D. Picard, L. Helsen, D. Saelens, Openideas - an open framework for integrated district energy simulations, in: 14th International Conference of IBPSA, Hyderabad, India, 2015.

- [39] E.-J. Kim, X. He, J.-J. Roux, K. Johannes, F. Kuznik, Fast and accurate district heating and cooling energy demand and load calculations using reduced-order modelling, *Applied Energy* 238 (2019) 963–971. doi:10.1016/j.apenergy.2019.01.183.
- [40] L. G. Swan, V. I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, *Renewable and Sustainable Energy Reviews* 13 (8) (2009) 1819–1835. doi:10.1016/j.rser.2008.09.033.
- [41] M. Wetter, M. Fuchs, P. Grozman, L. Helsen, F. Jorissen, M. Lauster, D. Mller, C. Nytsch-Geusen, D. Picard, P. Sahlin, others, IEA EBC annex 60 modelica library-an international collaboration to develop a free open-source model library for buildings and community energy systems, in: *Building simulation*, 2015.
- [42] N. Lauzet, B. Morille, T. Leduc, M. Musy, What is the required level of details to represent the impact of the built environment on energy demand?, in: *International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, Thessaloniki, Greece, 2016*.
- [43] C. Ribault, M. Bouquerel, A. Brun, M. Schumannb, G. Rusaouen, E. Wurtz, Assessing tools relevance for energy simulation at the urban scale: towards decision-support tools for urban design and densification, *Energy Procedia* 122 (2017) 871–876, cISBAT 2017 International Conference Future Buildings & Districts Energy Efficiency from Nano to Urban Scale. doi:10.1016/j.egypro.2017.07.452.

- [44] G. Plessis, A. Kaemmerlen, A. L. Amy Lindsay, BuildSysPro: a Modelica library for modelling buildings and energy systems, in: the 10th International Modelica Conference, Lund, Sweden, 2014.
- [45] G. Plessis, A. Kaemmerlen, A. L. Amy Lindsay, BuildSysPro: une bibliothèque Modelica opensource pour l'énergétique des bâtiments et des quartiers, in: Conférence IBPSA France, Marne la Vallée, France, 2016.
- [46] S. Bontemps, A. Kaemmerlen, G. Blatman, L. Mora, Reliability of dynamic simulation models for building energy in the context of low-energy buildings, in: 13th Conference of International Building Performance Simulation Association, Chambéry, France, 2013.
- [47] S. Bontemps, L. Mora, M. Schumann, Validation expérimentale appliquée la modélisation d'une cellule test de type basse consommation, in: Conférence IBPSA France, Marne-la-Vallée, France, 2016.
- [48] L. Merlier, L. Frayssinet, K. Johannes, F. Kuznik, On the impact of local microclimate on building performance simulation. part i: Prediction of building external conditions., Building Simulationdoi :10.1007/s12273-019-0507-7.
- [49] L. Merlier, L. Frayssinet, K. Johannes, F. Kuznik, On the impact of local microclimate on building performance simulation. part ii: Effect of external conditions on the dynamic thermal behavior of buildings, Building Simulationdoi :10.1007/s12273-019-0508-6.
- [50] J. Tardif, F. Diaz-Gonzalez, M. Kegel, A. Sola, J. Salom, A co-simulation framework for assessing the interaction between heat pumps and the

- low voltage grid on a district scale, in: Sixteenth International IBPSA Conference,, 2019, pp. 3242–3249.
- [51] V. Galtier, S. Vialle, C. Dad, J.-P. Tavella, J.-P. Lam-Yee-Mui, G. Plessis, Fmi-based distributed multi-simulation with daccosim, in: SpringSim, 2015.
- [52] F. Pedrinis, Représentations et dynamique de la ville virtuelle [french], Ph.D. thesis, Université Lyon 2 Lumière (2017).
- [53] U. Rochard, S. Shanthirablan, C. Brejon, M. C. le bras, Bâtiments résidentiels - Typologie du parc existant et solutions exemplaires pour la rénovation énergétique en France [french], Tech. rep., POUGET consultants (2015).
- [54] A. Grandjean, Introduction de non linéarités et de non stationnarités dans les modèles de représentation de la demande électrique résidentielle [french], Ph.D. thesis, Paris, ENMP (2013).
- [55] D. Robinson, U. Wilke, F. Haldi, Multi agent simulation of occupants presence and behaviour, in: Proceedings of building simulation, 2011, pp. 2110–2117.
- [56] N. Pflugradt, U. Muntwyler, Synthesizing residential load profiles using behavior simulation, Energy Procedia 122 (2017) 655–660, cISBAT 2017 International ConferenceFuture Buildings & Districts Energy Efficiency from Nano to Urban Scale. doi:10.1016/j.egypro.2017.07.365.
- [57] T. Huraux, N. Sabouret, Y. Haradji, Study of Human Activity Related

- to Residential Energy Consumption Using Multi-level Simulations., in: ICAART (1), 2015, pp. 133–140.
- [58] Q. Reynaud, Y. Haradji, F. Sempe, N. Sabouret, Using Time Use Surveys in Multi Agent based Simulations of Human Activity, in: Proceedings of the 9th International Conference on Agents and Artificial Intelligence, Vol. 1, 2017, pp. 67–77.
- [59] M. Wetter, C. van Treeck, New Generation Computational Tools for Building & Community Energy Systems, Tech. Rep. Annex 60 Final Report, International Energy Agency (2017).
URL <http://www.iea-annex60.org/downloads/iea-ebc-annex60-final-report.pdf>
- [60] T. Berthou, Développement de modèles de bâtiment pour la prévision de charge de climatisation et l’élaboration de stratégies d’optimisation énergétique et d’effacement [french], Ph.D. thesis, Ecole Nationale Supérieure des Mines de Paris (2013).
- [61] L. Frayssinet, T. Berthou, B. Duplessis, J.-P. Tavella, F. Kuznik, J.-L. Hubert, J.-J. Roux, Incertitude de simulation à l’échelle du quartier : comparaison de deux modèles et analyse de sensibilité [french], in: Conférence IBPSA France, 2018.
- [62] I. Hijazi, Integrated management of indoor and outdoor utilities by utilizing BIM and 3dgis, Ph.D. thesis (2011).

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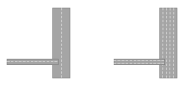
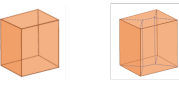

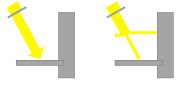



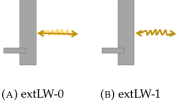
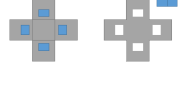
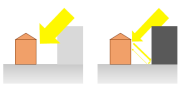
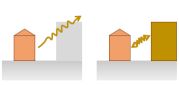

Model option	Meaning
Wall model	
Wall discretization $[Cond-] \tau_1 / \tau_2 < \text{or} > 1$ $\tau = 900s / \tau = 59s \text{ or } 15d$	
BEM - Building model	
Thermal zones $[Zoning-] 0 / 1$ One / One by orientation	
Controlled temperature $[Control-] 0 / 1$ Air temp. / Operative temp.	
Allocation of solar flux $[tr.Sol-] 0 / 1$ On the floor / Distributed	
Internal long wave $[intLW-] 0 / 1$ Air temp. / Operative temp.	
Internal walls $[Inertia-] 0 / 1$ Included / Neglected	
External CHTC $[extConv-] 0 / 1$ Fixed / Wind-dependent	
External long wave $[extLW-] 0 / 1$ Linearized / Complete	
Envelope representation $[EqEnv-] 0 / 1$ Explicit / Equivalent wall	
DEM - Interactions between buildings	
Solar masks and reflection $[Solar-] 0 / 1$ Neglected / Accounted for	
External long wave $[LWRad] 0 / 1$ Ground and sky / + Buildings	
Adjoin buildings $[Adjoin-] 0 / 1^{38}$ Adiabatic / Balance	

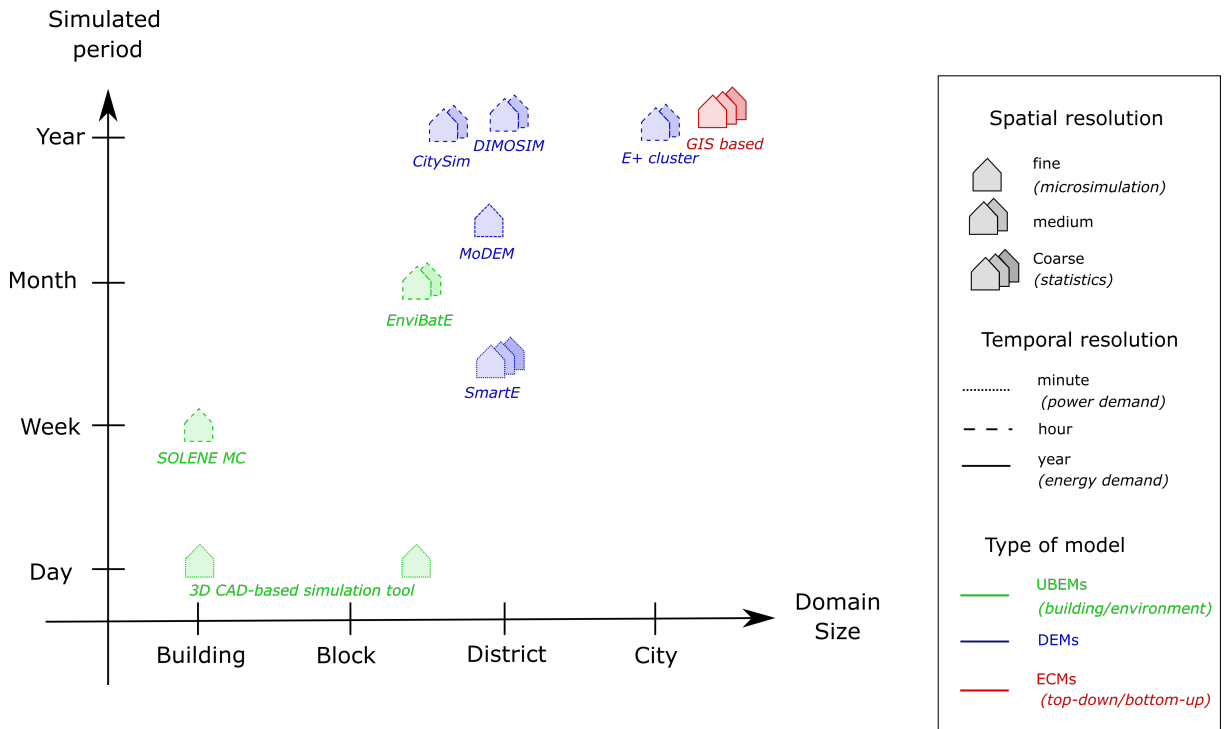
Table 1: Tested model adaptations

Building component	U – value [$W \cdot m^{-2} \cdot K^{-1}$]
Wall	1.7
Roof	3.2
Windows	2.8
Ventilation	$[vol^{-1}]$
Natural	0.5

Table 2: Building thermal properties

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References

3D-CAD based (He et al., 2009)	EnviBatE (Gros et al., 2014)	DIMOSIM (Riederer et al., 2015)
3D-CAD based (Kawai et al., 2014)	Smart-E (Berthou et al., 2015)	E+ cluster (Tian et al., 2015)
SOLENE MC (Bouyer et al., 2011)	CitySim (Orehounig et al., 2010)	GIS (Swan et al., 2008)

Figure 1: Comparison of the domains of availability of the different categories of energy simulation of urban buildings.

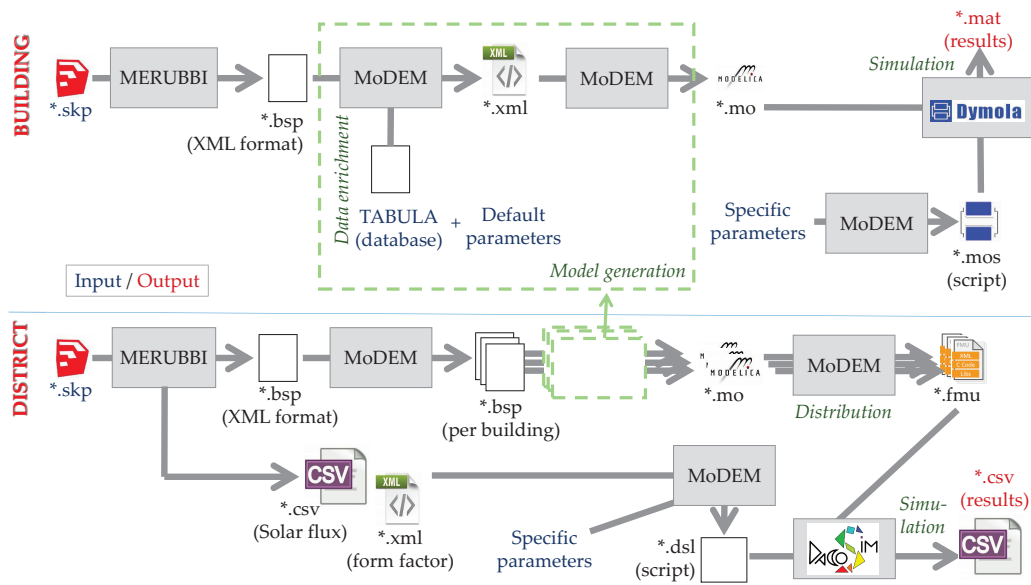


Figure 2: Detail of the tool-chain



Figure 3: Geometry of the use case

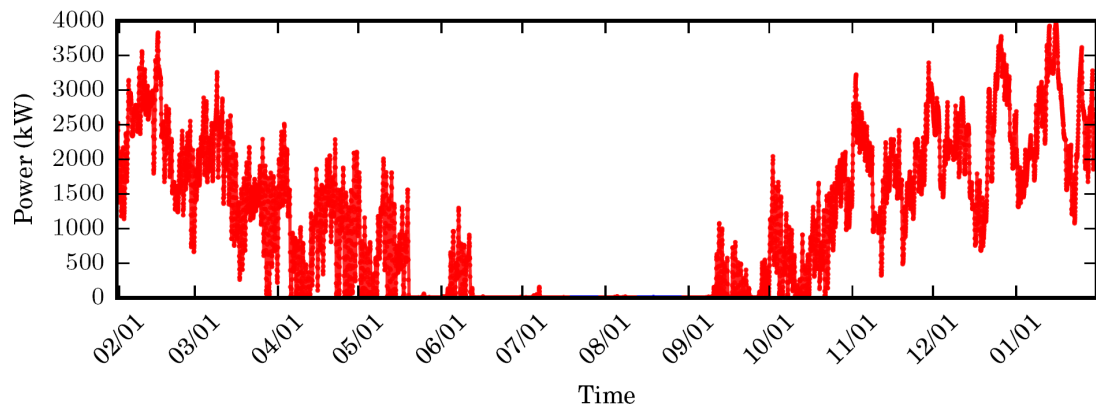
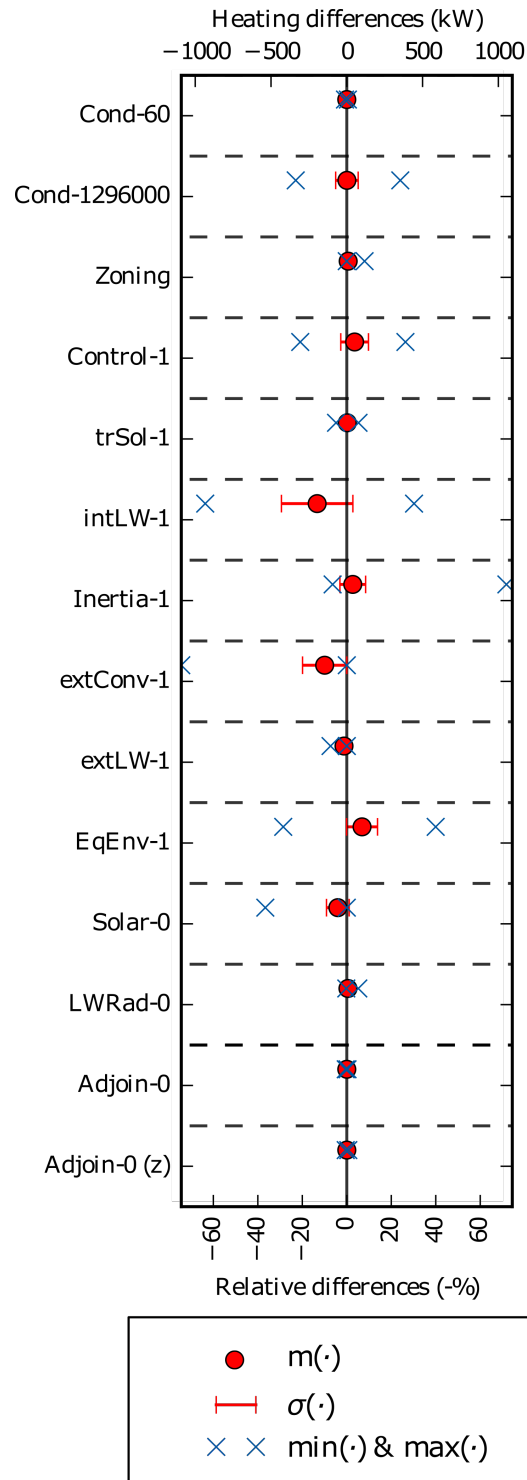


Figure 4: Simulated load curve for the district reference model



45
 Figure 5: Relative effects [kW and %] of model adaptations to heating on the mean $m(\cdot)$ standard $\sigma(\cdot)$ and maximal $\max(\cdot)$ / minimal $\min(\cdot)$ deviations

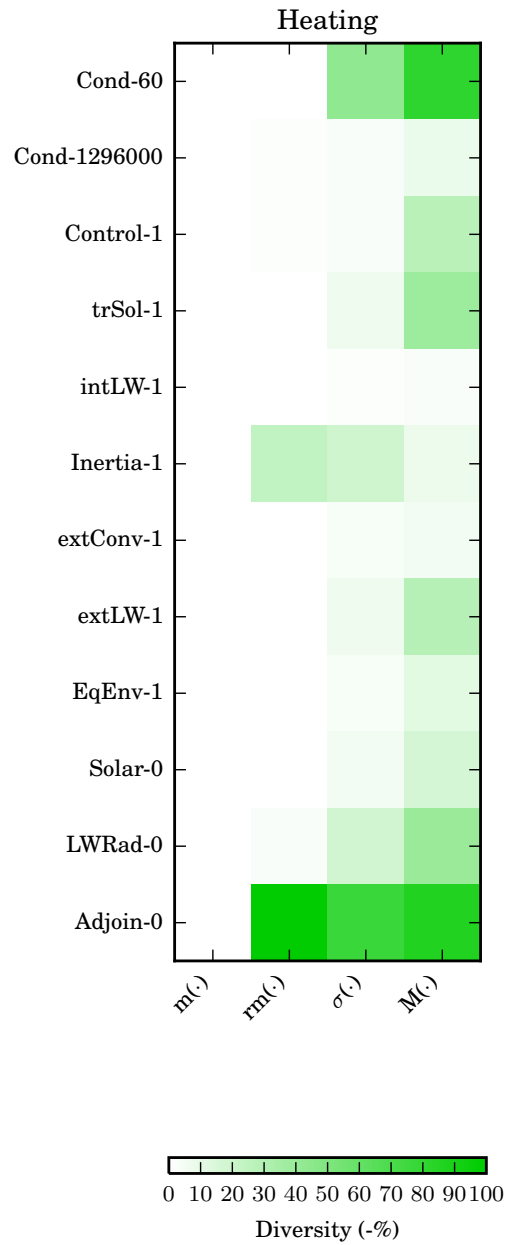


Figure 6: Relative effects of diversity (%) on the computed heating loads depending on the considered adaptation - mean value $m(\cdot)$; root mean square $rm(\cdot)$; standard deviation $\sigma(\cdot)$ and maximum value $M(\cdot)$